Chapter 3
Growth Rates and Wood Quality

Substantial effort and expense are involved in the establishment and **management** of forest plantations. There would be no point in growing them unless they provide something of value to the plantation grower, either as a financial return or otherwise. As discussed in Sect. 1.2, the value of plantations may arise from the wood products they produce or the environmental benefits they confer. However, in keeping with the general approach of this book (Sect. 1.3), this chapter will concentrate on wood production.

From this perspective, several things determine the financial return that an investor can expect from a forest plantation:

- The rate at which it grows—the faster it grows, the earlier can the plantation is harvested and the larger will be the quantities of the products that can be harvested from it.
- The quality of the wood it produces—that is, the better suited is the wood for the products to be produced ultimately from it (Sect. 3.3), the more ready will the market be willing to purchase it and the higher the price will it pay.
- The costs involved in establishing and managing it—these are determined by the labour market in the region where the plantation is being grown, the prices of the things needed for establishment and management (seedlings, fencing, fertiliser and so on) and the costs of the research and development the grower has undertaken.
- The prices received for the products that are sold from it—these are determined both by their quality and by the general economic circumstances of the market for timber within which the plantation operates.

The economic issues that surround the costs and returns involved in plantation enterprises, as alluded to in the last two of these dot points, are more properly the realm of text books on forest **economics** or management (e.g. Davis et al. 2001; Bettinger et al. 2009; Zhang and Pearse 2011; Wagner 2012). This chapter will not consider these economic issues further, but will concentrate on the biological issues of the growth rates of plantations and on the quality of the wood that is produced from them.

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To assess growth rates, a plantation owner will need some way of measuring and expressing them. Section 3.1 discusses the ways in which this is done in forestry. An owner will usually wish to assess how well a plantation is growing in relation to other plantations in the region, or indeed to other plantations elsewhere in the world; this will tell him or her how well the plantation is performing in comparison with the best practices used elsewhere. Plantation growth rates around the world are discussed in Sect. 3.2. Many different characteristics of wood determine its suitability for different uses. Section 3.3 describes those characteristics that are most important in determining its quality. These issues of growth rate and wood quality, and how they are influenced by plantation silviculture, will be referred to continuously in later parts of this book.

3.1 Expressing Growth Rates of Plantations

The rate of growth of trees in a plantation depends on the species planted, the environmental circumstances of the site on which it is planted and the silvicultural practices that are employed. Much of the substance of this book is concerned with these three issues.

Certain conventions are used in forestry science to describe forest growth rates and these will be described here using an example, again for flooded gum (*Eucalyptus grandis*) plantations in subtropical eastern Australia (Sects. 2.3, 2.4). Figure 3.1 is reproduced from my textbook on forest measurement (West 2009). Figure 3.1a shows the change with age in the wood volume contained in the stems of the trees of a typical flooded gum plantation stand. The shape of this growth curve is typical for forests and, indeed, for many other biological organisms; the growth rate increases with time initially (up to about 15 years of age in the figure) and declines steadily thereafter.

Given a growth curve like that of Fig. 3.1a, stand growth rate is usually expressed in one of two ways. The first is called **current annual increment** (often abbreviated as CAI and also termed periodic annual increment, or PAI). It is the immediate growth rate of the stand at any age. It changes with age and is illustrated by the solid line in Fig. 3.1b. It shows the increase in growth rate, to a maximum at about 15 years of age as mentioned in the preceding paragraph, with a progressive decline thereafter.

The pattern of change with age in current annual increment evident in Fig. 3.1b is typical for plantation forests anywhere in the world (and indeed for many native forests). The period whilst the growth rate is increasing, up to 15 years of age in the example, is the period when the trees are growing to the stage that the leaf and fine-root stand biomasses become more or less constant (Sects. 2.2, 2.3). The steady decline in growth rate after the maximum is reached is of great interest to forestry. If it did not happen, if growth continued at a constant rate instead of declining, forests would yield much more timber at much earlier ages.

The principal theory to explain the decline is known as the ‘hydraulic limitation’ theory. This proposes, first, that as a tree grows taller there is a longer path

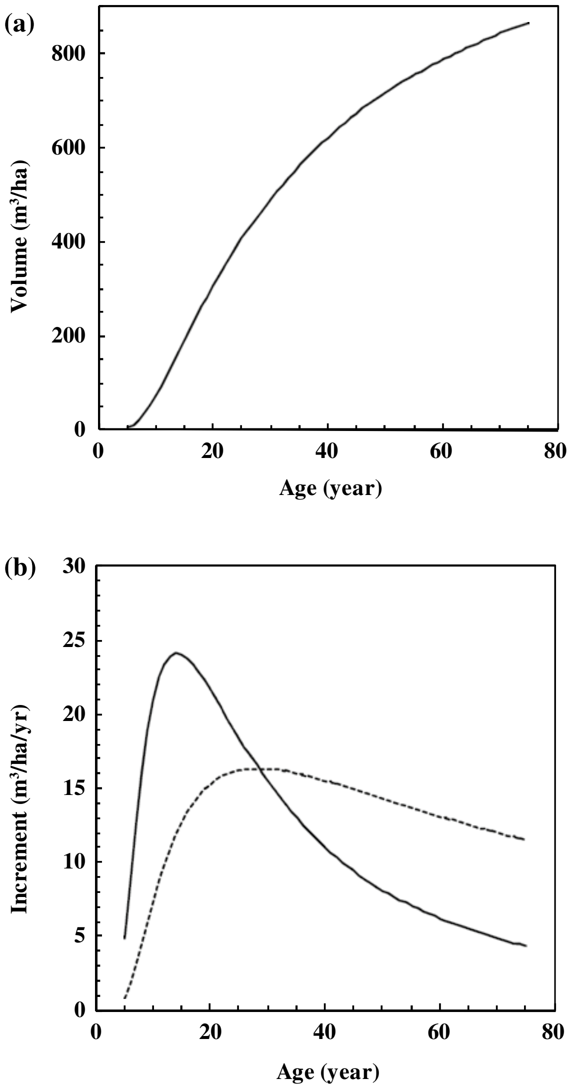


Fig. 3.1 (**a**) Change with age in the wood volume contained in the stems of the trees of a typical flooded gum (*E. grandis*) plantation stand in subtropical eastern Australia. (**b**) Change with age in current annual increment (——) and mean annual increment (- - - -) in stand stem wood volume for the stand shown in (**a**) (reproduced from Fig. 8.4 of West 2009)

through which water must travel from the roots to the leaves; this offers an ever increasing resistance to the flow, due to friction with the walls of the wood cells through which the water passes. Second, the taller the tree, the greater is the gravitational effect resisting the upward movement of water. These effects lead to a higher level of water stress in the leaves from time to time. The leaves then reduce their degree of stomatal opening from time to time. In turn, this reduces the amount of photosynthesis a tree can carry out and, hence, its growth rate. Ryan et al. (2006) have reviewed the research that has been done to test this theory. It appears to hold well for many tree species under many circumstances, but a

number of issues around it remain to be explained. Research has continued to test the theory further (Martínez-Vilalta et al. 2007; Bond et al. 2007; Martínez-Vilalta et al. 2007; Mencuccini et al. 2007; Vanderklein et al. 2007; Domec et al. 2008; Nabeshima and Hiura 2008; Sperry et al. 2008; Ambrose et al. 2009; Fernández and Gyenge 2009; Drake et al. 2010, 2011; Patankar et al. 2011; Piper and Fajardo 2011; Cramer 2012; Räim et al. 2012; Xu et al. 2012).

A second method used to describe stand growth rate in forestry is called **mean annual increment** (often abbreviated as MAI). This is the average rate of production to any particular age of the stand. It is determined simply as the growth (stand stem wood volume in the example) divided by the age at which the growth is measured. It is probably the most popular measure used by foresters to indicate how fast a forest grows. Mean annual increment changes with age during the life of the forest; it is illustrated by the dashed line in Fig. 3.1b.

Because both current and mean annual increments change with age, it is important to mention what age is being referred to when using them to describe the growth rate of any plantation. It is common also when referring to growth rates, that foresters will refer to the amounts of wood that can be harvested and sold from a forest (often called the merchantable volume), rather than to the total stem wood volume. These amounts may even be subdivided further into particular log size classes (Sect. 2.4). If this is being done, it is obviously important that the log class sizes be defined carefully, so it is quite clear what wood volumes are being referred to when expressing a plantation growth rate. Of course, growth rates of things other than stem wood volume, things like stand biomass, are often considered by forest scientists; the same conventions are used to describe their growth rates.

3.2 How Fast Do Plantations Grow?

Perhaps surprisingly, there is a rather limited amount of published information available to give a very reliable answer as to just how rapidly plantations around the world can grow. Pandey (1983) collated a large amount of growth data from the tropics. Mead (2013) summarised typical growth rates observed in plantations of various species around the world.

Figure 3.2 shows results from both Pandey's work and some other reports published since his work. Only measurement data from rapidly growing plantations of hardwood species have been included there. The figure shows how mean annual increment in stand stem wood volume of live trees (inclusive of any volume removed during the life of a stand by **thinning** the stand, that is, by removing some of the trees from the stand—Chap. 8) varies with age in those data. In all cases, the data were obtained from plantations that had been planted with a stocking density more or less normal for commercial plantations grown for wood production, say in the range 800–2,500 trees per hectare. Some of the plantations had been measured on several occasions and the trajectories of growth of those are shown as solid lines. Some had been measured once only and their results are

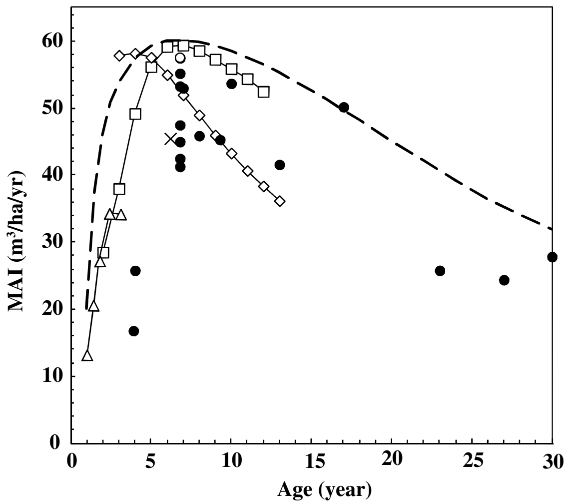


Fig. 3.2 For fast-growing hardwood plantation forests around the world, a scatter plot of published values of mean annual increment (*MAI*) in stand stem wood volume of live trees, inclusive of any volume removed at thinnings, against age. Plantations for which information was reported at several ages are shown as (——) and those with information for a single age as (●). Specifically identified plantations are (×) *E. grandis* in Hawaii, USA (see Fig. 3.3), (O) *E. dunnii*, *E. saligna* and *E. smithii* in Africa (each with the same result) (Schönau and Gardener 1991), (△) *E. grandis* in Australia (Cromer et al. 1993a), (□) *Falcataria moluccana* (formerly known as *Albizia falcataria*) in Indonesia (Pandey 1983) and (◇) *Gmelina arborea arborea* in Africa (Pandey 1983). The dashed line (– – –) was positioned by eye by the present author as an approximate world maximum for hardwood plantations (*Sources*—Bradstock 1981; Pandey 1983; Frederick et al. 1985a, b; Beadle et al. 1989, 1995; Schönau and Gardener 1991; Birk and Turner 1992; Cromer et al. 1993a; J.B. Friday 2005, personal communication; Tullus et al. 2012)

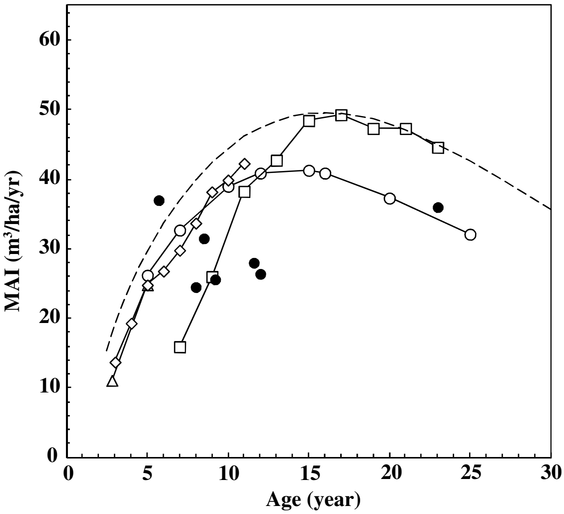
shown as single points. The results include data from plantations in Africa, India, Asia (Indonesia, Philippines), Oceania (Australia, New Zealand), Hawaii and South America. Most of the data are for eucalypt species, with some from other hardwood species (*Acacia dealbata*, *Falcataria moluccana*, *Gmelina arborea* and *Tectona grandis*). Figure 3.3 illustrates one of the plantations.

The results suggest that the mean annual increment of the fastest growing hardwood plantations increases rapidly to a maximum of about 60 m^3/ha/year at about 6–7 years of age, then declines steadily to just over 30 m^3/ha/year at 30 years of age. I positioned the dashed line in Fig. 3.2 to represent an upper limit to hardwood plantation growth rates around the world. It might be considered as an approximate world maximum, by which the growth rate of a hardwood plantation can be judged. Results for some particularly fast-growing species are identified specifically in the figure; those shown for flooded gum (*E. grandis*) in Australia (Cromer et al. 1993a) are from the example plantation used in Sect. 2.3.

Figure 3.4 shows similar data, but for softwood plantation species. The results include data from plantations in Africa, India, Asia (Indonesia), Central and South

Fig. 3.3 An example of a hardwood plantation forest that is growing relatively rapidly by world standards. It is a 6-year-old plantation of flooded gum (*E. grandis*) growing in Hawaii, USA; it is shown as the symbol (×) in Fig. 3.2. The stand contained 1,210 trees per hectare. Their average diameter at breast height over bark was 18 cm and their average height was 20 m (measured by J.B. Friday, University of Hawaii) (Photo—West)

Fig. 3.4 Results, similar to those of Fig. 3.2, for fast-growing softwood plantation forests around the world. Specifically identified plantations are (O) *Cupressus lusitanica* in Africa (Pandey 1983), (◇) *Pinus elliottii* in South America (Pandey 1983), (□) *P. patula* in Africa (Pandey 1983) and (△) *P. radiata* in Australia (Myers et al. 1996, 1998) (*Sources*—Lewis et al. 1976; Pandey 1983; Myers et al. 1996, 1998; Toro and Gessel 1999)



America and Australia. Most of the data are for species of pine (*Pinus*) with some from two other softwood species (*Cryptomeria japonica* and *Cupressus lusitanica*).

The world maximum for softwood plantations, shown by the dashed line in Fig. 3.4, suggests that the growth pattern for fast-growing softwood plantations is somewhat different from that for hardwoods. Early growth of softwoods rises to a maximum mean annual increment of nearly 50 m^3/ha/year at about 15–17 years of age, 9–10 years later than the age at which the maximum for hardwood plantations is reached. It then declines steadily to just over 35 m^3/ha/year at 30 years of age.

These world maxima should be useful guides for plantation growers to indicate how well their plantations are performing in relation to the fastest growing plantations in the world. However, a number of things must be borne in mind when using them:

- They refer to plantations being grown for timber production and established at stocking densities of about 800–2,500 trees per hectare. Plantations grown under other circumstances may have higher or lower growth rates. For example, one of the highest values of mean annual increment reported for plantations in the scientific literature is a value of about 100 m^3/ha/year, to 3 years of age, for the stem wood volume of a small experimental plantation of swamp gum (*Eucalyptus ovata*) growing in New Zealand (Sims et al. 1999). This is a growth rate far in excess of the value of about 54 m^3/ha/year, to 3 years of age, for the hardwood world maximum shown in Fig. 3.2. This was a plantation being grown for **bioenergy** production and there are several reasons why its growth rate was so much higher than those shown in Fig. 3.2; these are discussed in more detail in Sect. 5.5.1. No doubt world maxima for growth rates of bioenergy plantations will be developed as more and more growth data are published from them; they are likely to be well above the maxima shown in Figs. 3.2 and 3.4.
- Different species will have different patterns of growth rate over their lifetimes. Some will grow rapidly early in their lifetime, perhaps approaching the world maximum for some years, then may slow their growth rate and fall below it. This growth pattern is illustrated by the results in Fig. 3.4 for *C. lusitanica* in Africa. Other species may grow more slowly early in their lifetime, but then maintain a relatively high growth rate later in life and reach the world maximum at later ages. The results in Fig. 3.4 for *Pinus patula* in Africa illustrate that trend. The growth rate pattern that different species adopt can be very important when choosing what species is to be planted at a particular site. If the plantation is to be grown to produce only small trees, say for paper-making or for bioenergy, a species that grows rapidly early in its lifetime would be preferred, so that as much as possible of the desired product would be available as early as possible. However, if the plantation is being grown to produce much larger logs for sawing into timber, a species that maintains a higher growth rate later in its lifetime might be preferred.
- Plantations would be expected to grow at rates as fast as the world maxima only under very special circumstances. The temperature regime at the site would have to be close to an optimum that maximises the metabolic activity of the species concerned (Sect. 2.1.3). The site would need to have a plentiful rainfall (or perhaps even be irrigated), together with a soil capable of storing adequate

moisture to ensure the trees always have a more than adequate water supply (Sect. 2.1.2) for all the year. The soil would have to be very fertile (and perhaps supplemented by fertiliser) to ensure the trees have a more than adequate supply of nutrient elements (Sect. 2.1.4). Lastly appropriate silvicultural practices must have been applied at the site to ensure the trees can avail themselves of all the resources available at the site. Few sites anywhere in the world have all these desirable characteristics and so most plantations can be expected to have growth rates somewhat below the world maxima.

3.3 Wood Quality

World markets for industrial wood (Sect. 1.1) are becoming increasingly discriminating of the quality of the wood that is sold to them. The principal industrial products produced from wood are (Shmulsky and Jones 2011):

- Timber—this consists of boards sawn from logs that have been cut from tree stems. Timber has a multitude of uses, for furniture, flooring, panelling, framing, boxes, pallets, railway sleepers and many other things. When cut fresh from the log, wood contains a lot of water. If it is put into service without drying, it will shrink and warp. To avoid this, usually it is dried before it is sold, either by being left out in the air for some months or by being heated for some hours in a kiln. Wood is a rather variable material that requires a high level of skill and advanced technology to ensure it is both sawn and dried successfully. Larger pieces of timber can be manufactured from smaller pieces cut from smaller logs. These can be finger-jointed and glued together, to make longer boards, or many can be glued together to make very large laminated beams.
- Plywood—this is a panel product, manufactured by gluing together several layers of thin veneer. Plywood has many and varied uses, especially in building. Veneers of wood with attractive grain are often glued to panels to make feature wall panelling. Veneer is produced either by peeling, with a large blade, a thin layer from a log mounted in a lathe or by slicing strips from the log.
- Particle-based panels and timber—in manufacturing these, wood waste or small logs are broken down into small pieces that are then glued and pressed into large sheets or boards. The small pieces can be chips, flakes, shavings, sawdust or slivers, all of which can be used to make boards with different properties. Often these products can be made from the waste left after producing timber.
- Other fibre products—these include hardboards, insulation boards and others, where, in effect, pulp (see paper, below) is pressed and dried to form large panels.
- Round wood products—these include poles, posts, piles and others, where the tree stem is simply cut into lengths. Often these products are impregnated with preservative chemicals; these prevent rotting and decay when the products are in use, especially where they are sunk partly into the ground or are used in water. Other forms of timber that are to be exposed in use are often treated also with preservatives.

- Paper—where wood is first macerated mechanically or chemically to separate its individual fibres (Sect. 3.3.1) to make pulp. The pulp is then ground further and mixed with water to form a thin mat. The water is drained from the mat that is then pressed, rolled and dried to form paper. There is an enormous variety of papers, from strong cardboards for packaging to very high-quality papers for fine printing.

The properties that make wood most suitable for paper production, say, are rather different from those required of wood to be sawn to produce timber. The study of wood, its properties and its conversion to wood products is a specialised field of study, far too large to consider in detail in this book. However, the various silvicultural practices used in plantation forestry that are the subject of this book can affect appreciably the quality of the wood produced (Sect. 3.4).

Growers may wish to know whether or not wood of a quality appropriate for its intended use is indeed being produced whilst the trees are still growing in the plantation. Various techniques have been developed to allow this, either by affixing instruments to the tree stem, by taking a small wood samples from the stem, or by measuring various stem or branch characteristics either directly or with various forms of instrumentation (Downes et al. 1997; Schimleck et al. 1999, 2005; Raymond et al. 2004, 2010; Joe and Dickson 2006; Moberg 2006; Warren et al. 2009; Briggs 2010; Callister and England 2010; Johnstone et al. 2011; Pfautsch et al. 2012).

The remainder of this section will describe briefly some of the properties of wood that are important in determining its quality for industrial end uses. Only some of the more important properties are described; fuller discussion can be found in texts on the subject (e.g. Desch and Dinwoodie 1996; Shmulsky and Jones 2011).

3.3.1 Tracheid and Fibre Length

About 90–95 % of the wood (xylem) of the stems of softwood trees is made up of cells (Sect. 2.1.1) known as tracheids. These are long (averaging about 3–4 mm, which is long by wood standards), thin (diameter about 0.025 mm) cells arranged with their long axes vertically in the stem. Like most cells of wood (Sect. 2.1.1), they are dead cells that have lost their cell contents and retain only their cell walls. They are joined one to the other by holes through their walls, known as pits. They provide the structural strength to softwood tree stems and allow water to be transported up the stem, passing from tracheid to tracheid through their pits (making the pipes referred to in Sect. 2.1.2). Softwood xylem does contain some living cells, known as parenchyma, that act as food-storage tissue for the tree and may produce resin. Some softwoods also contain relatively large, hollow resin ducts (Desch and Dinwoodie 1996).

The principal structural support of hardwood tree stems is provided by cells known commonly as fibres. These are anatomically similar to, and have much the same diameter as, tracheids in softwoods; however, they are much shorter (usually a little under 1-mm long). Depending on the species, fibres make up 15–60 % of the wood of hardwoods. However, water transport through hardwood tree stems is principally through hollow cells known as vessels. Vessels are shorter than fibres

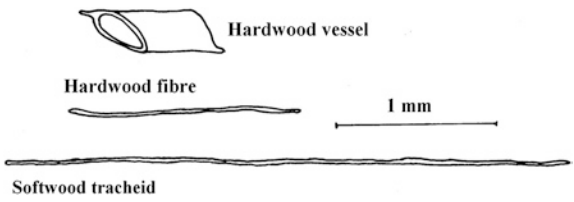


Fig. 3.5 Relative sizes of principle types of cells that make up the xylem of hardwoods and softwoods. Note that in the living tree, these cells are arranged parallel to the axis of the stem, branch or woody root (after Shmulsky and Jones 2011)

(around 0.2–0.5-mm long), but have much larger diameters (varying over the range 0.02–0.4 mm). They are often large enough in diameter to be seen with the naked eye in a cross-section cut from a hardwood tree stem.

Vessels are commonly arranged one above another in the stem to make long pipes up which water can pass. Depending on the species, vessels make up 20–60 % of the wood of hardwoods. The presence of excessive numbers of vessels in wood can affect the quality of paper (Higgins 1984; Downes et al. 1997) and particle-based boards (Macmillan 1984) because they sometimes come loose from otherwise smooth surfaces. Hardwood stems also contain living parenchyma and may also have resin or gum ducts.

Figure 3.5 illustrates the relative sizes of vessels and fibres in hardwoods and tracheids in conifers. Fibre or tracheid length varies substantially between different tree species and also varies within the stem of individual trees, both vertically up the stem and horizontally across its cross-section (Higgins 1984; Hillis 1984; Downes et al. 1997; Raymond et al. 1998; Mäkinen et al. 2002c; Watson et al. 2003). The length of the tracheids or fibres is particularly important in paper-making. It affects the extent to which they weave together to form the final paper and, hence, its strength. Because softwood tracheids are longer than hardwood fibres, papers that require strength (such as packaging papers, cardboards or newsprint) tend to be made with high proportions of softwood pulp. Very high-quality printing papers often contain more hardwood pulp. Various other wood characteristics, not just fibre length, are also important in paper manufacture and some of these will be alluded to in the following subsections. However, paper-making is a complex process and many factors, not just wood quality, determine the final paper quality. Because other fibre products (hardboards, insulation boards and others) are produced from pulped wood, fibre or tracheid length can affect their properties also (Macmillan 1984).

3.3.2 Microfibril Angle

Microscopic examination of the walls of wood cells shows that they are made up of long strands called microfibrils that are so small can be seen only with the very high magnification of an electron microscope. In turn, microfibrils consist of many

strands of a substance called **cellulose**. Chemically speaking, cellulose is a complex carbohydrate, consisting of many sugar molecules strung together in a long sequence. Microfibrils are bound together in the cell wall by a substance called lignin. Lignin has a complex chemical structure that has not yet been fully determined. In effect, lignin can be thought of as being like cement and microfibrils as steel reinforcing rods embedded in it (Downes et al. 1997; Déjardin et al. 2010). Cellulose and lignin are the two most abundant organic chemicals (that is, chemicals relating to or derived from living organisms) on earth, because about 50 % of the dry biomass of plants is composed of them.

The microfibrils are wound spirally around the cell wall. The angle, from the long axis of the cell, at which they are wound determines the strength of fibres and tracheids, particularly their resistance to bending; the smaller the angle, the stronger the cell. In tree stems, the angle is often greater nearer the centre of the stem and declines towards the outer parts of the stem cross-section (Hillis 1984; Evans et al. 2000; Jordan et al. 2005). Wood with a high microfibril angle tends to have appreciably less strength when sawn and suffers more distortion when it is dried (Desch and Dinwoodie 1996; MacDonald and Hubert 2002). Little is known about the factors that control the microfibril angle in wood (Déjardin et al. 2010).

3.3.3 Wood Density

The density of wood (its weight per unit volume) is the characteristic used, perhaps most frequently to assist in the assessment of wood quality. It is usually expressed as **basic density**, which is the oven-dry weight of wood per unit volume of the undried (fresh) wood.

The dimensions of the cells that make up wood, that is, the thickness of their cell walls and the size of the empty space the walls surround, determine the **wood density** at any point in the stem. In hardwoods, the relative frequency of larger-diameter vessels when compared with smaller-diameter fibres can affect wood density. The average basic density of the wood in stems varies greatly from tree species to tree species around the world, over a range of about 200–1,200 kg/m^3, the range being appreciably wider in hardwoods than in softwoods (Desch and Dinwoodie 1996). Generally, the average density of wood is lower in stems of shorter-lived species that are adapted to grow rapidly in full sunlight during the early stages of the regeneration of native forests. Slower growing, longer-lived species, that are adapted to grow in the shade below the canopy of the faster-growing species, ultimately survive to form the mature native forest and tend to have stem wood of higher average density; Poorter et al. (2012) have given an interesting example of this. Larjavaara and Muller-Landau (2010) have proposed a mechanism to explain why this is so. We will not discuss that further here, but their proposal does suggest that faster growth is often associated with the production of lower density wood in tree stems; this is consistent with the discussion in Sect. 3.4

that it is the effects of silvicultural practices on tree growth rates that principally determines wood properties, including basic density.

Looking in finer detail at the wood in individual tree stems, it is found that basic density can vary considerably, both with height in the stem and across the stem cross-section. In some species, density increases from the inner to the outer part of the stem section, perhaps by as much as 100–150 kg/m^3. In other species, the reverse occurs, and in yet others, there is little change across the section.

Woodcock and Shier (2002) have advanced the interesting hypothesis that increases in wood density across stem sections tend to occur in the species that grow rapidly in full sunlight. The reverse occurs in the longer-lived, slower growing species that grow in the shade below the canopy. They suggested that the rapidly growing species produce low density wood initially, until they become tall enough to be at risk of blowing over or snapping off in the wind. They then produce denser wood on the outer parts of the stem to increase its strength, hence its ability to resist wind damage. The trees that grow more slowly in shade will already have much larger stems before they become tall enough to be at risk of wind damage and it is unnecessary for them to produce denser wood in the outer parts of the stem.

The species used for major plantation forestry developments around the world are commonly those that grow rapidly in full sunlight and, hence, are mainly species in which basic wood density tends to increase towards the outer parts of the stem. Examples of this have been given for various species in various parts of the world (Kellomäki et al. 1999; Evans et al. 2000; DeBell et al. 2001; MacDonald and Hubert 2002; Zamudio et al. 2002; Mäkinen et al. 2007; Mora et al. 2007; Ikonen et al. 2008; Schneider et al. 2008; Gardiner et al. 2011; Watt et al. 2011; Chowdhury et al. 2012; Guller et al. 2012).

Some of these works discuss also how density varies with height up the tree stem in these species. The stem cambium (Sect. 2.1.1) is progressively younger further up the stem (simply because trees grow progressively in height) and younger cambium produces less dense wood; in line with the engineering concepts of Woodcock and Shier's theory, there is less need for stronger wood near the tip of the tree, because the bending stresses exerted there by the wind are less than near the base of the tree. Often, there seems to be markedly less dense wood produced by the cambium for about 6–10 years and then density increases in outer layers of wood beyond that; this column of less dense wood up the centre of the tree stem is often termed juvenile wood. Both the age of the cambium and the stage of maturity of the tree affect the development of wood across the stem cross-section and with height up the stem (Burdon et al. 2004; Mora et al. 2007; Ikonen et al. 2008; Guller et al. 2012).

Not only does wood density tend to vary generally both across the stem cross-section and with height up the stem, it also varies at a very small scale across the stem cross-section because of seasonal growth of the trees (Shmulsky and Jones 2011). When seasonal conditions are most favourable for growth, when the weather is warmer or wetter, tree stems grow faster and less dense wood is produced; this is commonly called **earlywood** (or sometimes springwood). When

conditions are less favourable, growth is slower and denser wood is produced; this is termed **latewood** (or summerwood). The alternation of earlywood and latewood in tree stems makes their growth rings.

In some species, in cooler climates especially, growth rings are produced very regularly as the seasons change, one ring per year. Their ring widths can be used to estimate changes in weather conditions from year to year to reconstruct past climates (a discipline known as dendrochronology). In other species, and especially in more tropical areas where seasonal weather changes are not so marked, growth rings are still produced, but not necessarily at clearly defined annual intervals.

The small-scale differences in basic density across growth rings can be very large. Evans et al. (2000) used X-ray equipment to measure basic density at less than 0.5-mm intervals across stem sections of 15-year-old plantation-grown shining gum (*Eucalyptus nitens*) trees. They found that basic density differed by as much as 700 kg/m^3 between the least dense and densest part of some growth rings. Similarly, Bouriaud et al. (2004) found differences as large as 600 kg/m^3 across stem sections of 55-year-old trees of the hardwood beech (*Fagus sylvatica*), growing in native forests in France.

Wood density is considered as an important characteristic to help define wood quality because it correlates reasonably well with a number of the characteristics important in various end uses of wood. Denser wood tends to be stronger and stiffer, properties important for its use in construction. There is an increasing tendency around the world to harvest fast-growing, commercial plantations at younger and younger ages. This means that the wood will tend to contain an increasing proportion of less dense, juvenile wood. Yang and Waugh (1996a, b) found that logs from 19–33-year-old plantation-grown eucalypts could be sawn to produce high-quality structural timber, but the average strength of the sawn boards was lower in younger trees; hence, it was slightly less valuable commercially. Shmulsky and Jones (2011) have discussed the variety of problems that the presence of juvenile wood can lead to when processing timber.

The thicker cell walls of denser wood tend to contain larger amounts of water than the cell walls of less dense wood. This makes denser wood subject to more shrinkage when it is being dried in kilns for use in service (Desch and Dinwoodie 1996; Hillis 1984; Blakemore 2004). As well, the need to remove more water from it makes it more expensive to dry; however, because it is stronger, denser wood is less likely to suffer collapse of cells during drying and the development of small splits (commonly referred to as checks) in the dried wood (Ilic 1999; Oliver 2000).

The strength of particle-based panels and timber is determined more by the strength of the glue than by the strength of the wood; thus, less dense wood can be used to make panel products that are just as strong but are cheaper to press, cut and transport. Denser eucalypt wood has been found to be more difficult to peel when making veneer to produce plywood (Macmillan 1984).

Because it contains more wood per unit volume, denser wood tends to give a higher yield of pulp in paper-making. However, it is easier to collapse the thinner cells in less dense wood. This leads to better bonding between the cells when they are made into paper, which in turn, leads to stronger paper (Higgins 1984; MacDonald and Hubert 2002).

3.3.4 Grain Angle

The orientation of fibres and tracheids (Sect. 3.3.1) within the stem is known as the grain direction. When they are aligned parallel to the axis of the stem, the wood is said to be straight-grained. Commonly, they tend to be at a slight angle and, more extremely, may even be spirally arranged around the stem. In some cases the direction of the spiral changes as a tree grows over several years, when the tree is said to have interlocked grain (Desch and Dinwoodie 1996; Shmulsky and Jones 2011). The grain direction may vary systematically across the stem cross-section in some species (Hillis 1984; MacDonald and Hubert 2002).

Localised variations in grain direction, together with the changes in colour that occur with annual growth rings (Sect. 3.33) can lead to highly attractive grain features. These can be very important for the manufacture of high-quality furniture or in other timber to be used as a decorative feature. Different sawing patterns can be used to emphasise these highly desirable features of some timbers.

For more prosaic uses of timber, such as in construction, timber strength tends to decrease as the grain angle increases and the degree of distortion during drying tends to increase (MacDonald and Hubert 2002). These effects can be exacerbated, if the tree stem was bent during growth, because the angle of the grain in the sawn board will vary as the saw cuts straight through a bent stem; distortions during drying will then vary greatly at different distances along the board. For products where wood is reduced to small particles or is macerated (paper or particle-based panels and timber), grain angle is of little importance.

3.3.5 Sapwood and Heartwood

As the stem of a tree increases in diameter with age, it eventually contains more wood than is necessary to transport from the roots the water required by the leaves (Sect. 2.1.1). Older wood, closer to the stem centre, is then converted to what is known as heartwood, through which water is no longer transported. Sufficient sapwood is left in the outer part of the stem cross-section to provide the water-transport needs.

Heartwood is often darker in colour than sapwood. Its formation involves the deposition by the tree of a wide range of chemical substances known as polyphenols; because they can be extracted from heartwood by boiling in water, alcohol or other solvents, they are known also as extractives (Hillis 1984; Shmulsky and Jones 2011). These substances fill the empty cells in heartwood and are deposited in their walls. The blockage of the cells prevents any water transport through them. Any live parenchyma tissue (Sect. 3.3.1) dies.

Some of the extractives deposited in heartwood may be toxic to, or at least repellent to, fungi (Sect. 11.1) or insects (Sect. 10.2) (Shmulsky and Jones 2011). Fungi and insects can rot or decay timber in service, or even the stem wood in the

tree when it is still alive. Because of its resistance to rot and decay, heartwood may be much more durable in service than sapwood (Hillis 1984); the durability of both varies widely between species. The blockage of the cells in heartwood may make it more difficult to dry than sapwood. It may also make heartwood more difficult to penetrate with liquids, such as the anti-fungal or insecticide chemicals with which round wood products, such as posts, are often treated to preserve them when in use (Shmulsky and Jones 2011). Other extractives may affect pulping properties of wood, the adhesion of glues or the degree of shrinkage and collapse of cells during drying (Higgins 1984; Hillis 1984). However, the deposition of extractives does not affect the basic characteristics of cell walls or the basic density of the wood and so there is no difference in strength between timber sawn from heartwood or sapwood.

As fast-growing, commercial plantations are harvested at younger and younger ages, there will be an increasing need to deal with wood that contains a lower proportion of heartwood than has been usual in the past.

3.3.6 Reaction Wood

Trees that lean, or are bent by winds that blow consistently from one direction, develop what is known as reaction wood (Barnett et al. 2012). This is positioned eccentrically around the stem, reaching its greatest development in the direction of the force that promotes its development. Reaction wood is present consistently in branches that are bent normally under their own weight.

In softwoods, the reaction wood develops on the side of the stem or branch that is under compression (that is, on the side towards which the tree is leaning, on the side towards which it is being blown or on the under-side of branches) and is known as compression wood. In hardwoods, the reverse occurs and tension wood develops on the side of the stem or branch that is under tension (Shmulsky and Jones 2011). In some hardwood species, appreciable amounts of tension wood have been found in stems of vertical trees that do not seem to have been subjected to any excessive bending forces; this is probably a response to normal swaying in the wind (Washusen 2002; Washusen et al. 2002; Washusen and Clark 2005).

Compression wood is denser and darker in colour than surrounding tissues. Its tracheids tend to be shorter in length than in normal wood and the cell walls are more heavily lignified and have a higher microfibril angle, giving it reduced strength. When dried, compression wood shrinks far more than normal wood. This gives particular problems if a sawn board contains some compression wood; when dried, the excessive shrinkage of the compression wood may cause the board to bow (Desch and Dinwoodie 1996).

Tension wood contains fewer and smaller-diameter vessels than normal wood. It has a lower proportion of lignin in the cell walls and so tends to be paler in colour. The inner cell walls of its fibres have a gelatinous layer, made largely of cellulose. As with compression wood, tension wood has abnormally high shrinkage (Hillis

1984; Washusen et al. 2000a; Washusen and Evans 2001) and its cells may collapse when dried, causing further defect in timber (Bootle 1983). Its low lignin content means that fibres tend to be pulled out of the timber as it is sawn, rather than being cut cleanly; this leads to a more roughly cut surface (Desch and Dinwoodie 1996).

3.3.7 Growth Stresses

As a tree grows and wood cells form from the cambium (Sect. 2.1.1), the newly formed cells become stressed, a phenomenon in trees known as growth stress. The word 'stress' is being used here in an engineering sense, where an object is stressed when a force stretches, compresses or twists it; the stress is measured as the force applied per unit area of the object. When the stress on an object is relieved by removing the force causing it, the object returns to its original size and shape; the change in dimensions of an object caused by stress is known as **strain** (Raymond et al. 2004).

It is not known exactly how wood cells become stressed during their development (Wilkins 1986). Recent theories suggest that it has to do either with the way lignin is deposited as it binds microfibrils in the cell wall or as cellulose contracts as microfibrils are formed (Yang and Waugh 2001). Whatever their cause, the relief of growth stresses in tree stems when timber is sawn from them can cause such serious distortions in the sawn boards that they may be rendered useless. Even when the tree is first felled, relief of growth stresses can cause major cracks to appear right across the stem, extending for several metres up the tree (Page 1984; Kauman et al. 1995; Yang and Waugh 2001).

Different species vary greatly in the extent to which growth stresses occur within their stems. It has been thought generally that, as trees grow in diameter, the stresses within the stem are spread over larger areas; hence, the stresses tend to be less in the outer parts of the stems of large trees that can then be sawn with less damage occurring (Hillis 1984). So severe are the growth stresses towards the centre of stems in some species that the structure of the wood can be damaged for as much as one third of the width of the stem. This wood is known as brittleheart and is much reduced in strength (Hillis 1984; Desch and Dinwoodie 1996; Yang and Waugh 2001). However, more recent work with eucalypts (Raymond et al. 2004) has found that the distribution of growth stresses across stems can be highly variable and very difficult to predict for any particular tree stem.

Growth stresses are generally much less in softwoods than in hardwoods. Some eucalypts (which are hardwoods) are particularly renowned for their high levels of growth stress. This causes considerable damage to the quality of boards sawn from them, particularly in younger, plantation-grown trees (Yang and Waugh 2001; Yang et al. 2002; Chauhan and Walker 2004). However, the larger (that is, the faster-growing) trees in a plantation at a particular age may have a lower gradient of stress from the inner to the outer parts of the stem cross-section and, hence, show less damage in sawn boards (Wilkins and Kitahara 1991a, b).

Methods have been developed to assess and predict the level of growth stresses within stems of trees, even whilst they are still standing (Fourcaud and Lac 2003; Forcaud et al. 2003; Yang and Ilic 2003; Raymond et al. 2004; Yang et al. 2005). Various ways of handling stressed stems have been developed to minimise consequent damage during processing (Page 1984; Yang and Waugh 2001).

3.3.8 Knots

Where a branch has grown from the stem of the tree, a knot develops in the stem wood. Eventually, as the tree grows taller, branches on the lower part of its stem lose their leaves, die and are shed by the tree (Sect. 9.1). However, the knot remains in the stem wood, extending for a distance determined by the length of time the branch was held on the tree.

Knots can give a very attractive appearance to the surface of sawn timber and, in some species, can make the timber extremely valuable for the manufacture of the highest-quality furniture or panelling (Desch and Dinwoodie 1996). In general, however, knots are the chief source of defect in sawn timber, either in its structural strength or the quality of its surface appearance (Kellomäki et al. 1989; Waugh and Rosza 1991; Yang and Waugh 1996a, b; Washusen et al. 2000b; MacDonald and Hubert 2002; Yang et al. 2002; Wang et al. 2003; Pérez et al. 2003; Washusen and Clark 2005; Moore et al. 2009). Other sources of defect are the presence of gum or resin, splits, stem pith, sloping grain (Sect. 3.3.4), holes left by agents such as wood-boring insects or excessive taper or crookedness of the stem (McKimm et al. 1988; Waugh and Rosza 1991). These are less common problems than knots and will not be discussed further.

The larger the knot, the more likely it is to cause a serious defect in sawn wood. It is common in plantation forestry to remove branches by **pruning** to minimise the occurrence and size of knots. Pruning is discussed in detail in Chap. 9.

3.4 Silviculture and Wood Quality

As markets have become increasingly concerned about the quality of wood supplied by plantations, there has been increasing interest in the effects on wood quality of the environmental circumstances under which plantations are grown (Briggs 2010). These circumstances include site factors, such as soil fertility and climate, as well as the effects of the silvicultural practices which are applied to promote plantation growth.

At the cellular level, research has led to some understanding of the physiological processes and genetic control involved with wood development in tree stems (Kramer 2006; Eder et al. 2009; Déjardin et al. 2010; Du and Groover 2010; Risopatron et al. 2010). Based on this work, Downes et al. (2009) and Drew et al.

(2010) developed a model system to predict day-by-day wood cell tissue development in individual eucalypt tree stems. In the model, water availability and air temperature are considered to be the environmental factors most important in influencing wood development and determining tree growth rates. Both of these factors are assumed to affect photosynthetic production by the tree and production by young leaves of a plant **hormone** called auxin. Plant hormones are chemical substances that are produced naturally by plants and control certain of their growth processes. Auxin is one such hormone, known particularly for its effects in promoting cell enlargement; it is known to affect wood development in trees (Uggla et al. 2001). There are a number of other hormones that have various other effects on cell development.

In Drew et al's model, auxin is assumed to move from the leaves, down the tree stem to the cambium where wood is developing; the concentration of auxin reaching a particular point in the cambium determines the size that developing cells attain and, hence, wood density at that point in the stem cross-section. The model does not at present address how microfibril or grain angle develops. Models of wood development in some coniferous species do not operate at the fine detail of the day-by-day cell development model of Drew et al., but rather they predict development of individual wood rings within tree stems (Mäkinen et al. 2007; Ikonen et al. 2008; Savva et al. 2010; Gardiner et al. 2011).

Over the last decade or so, considerable research has aimed to elucidate how environmental changes affect the wood properties that are important for its use in practice. Particular attention has been paid to the effects on wood basic density (Sect. 3.3.3) and 'stiffness'. Wood stiffness is generally correlated with density (Yang et al. 2003; Lindström et al. 2004; Lachenbruch et al. 2010; Watt et al. 2010b); it defines the ability of wood to resist bending under load, clearly an important characteristic for wood to be used in building. It is measured as the modulus of elasticity of wood, defined in turn as the ratio of the bending pressure applied to a piece of wood (stress, as defined in its engineering sense in the Glossary) to the degree to which the piece of wood is bent (strain, in its engineering sense). The remainder of this section will concentrate on effects on wood basic density and stiffness.

It has become evident that environmental effects that accelerate tree stem diameter growth rates, whether due to site characteristics or silvicultural practices, lead often to the production of wood with reduced stiffness. As discussed in Sect. 2.1.1, a tree stem may be considered as a pole supporting the leaves and branches high in the air. To remain upright, a pole must have at least some minimum diameter at its base, a diameter that may be reduced as the stiffness of the material from which the pole is made increases. Thus, trees which grow larger in diameter, because of favourable environmental effects, will not require their stems to be made of wood with such high stiffness as slower growing trees. This effect has been observed in a wide range of plantation species, both softwoods and hardwoods, mostly reported as results from experiments where tree diameter growth rates were accelerated in stands established with wider initial spacing (Sect. 7.2) or from which trees had been removed by thinning (Chap. 8) (Watt et al. 2006, 2011;

Jiang et al. 2007; Roth et al. 2007b; Waghorn et al. 2007; Raymond et al. 2008; Schneider et al. 2008; Lasserre et al. 2009; Moore et al. 2009; Warren et al. 2009; Zhang et al. 2009b). However, the effect does not always occur and thinning has been reported to have had no effect on stiffness (Gagné et al. 2012). In such a case, faster-growing trees with larger diameters may well have far greater stem stiffness than they need to ensure that they remain upright; it is not uncommon for trees to have such a 'safety factor' built in (Osler et al. 1996b), so that their stem strength is greater than it needs to be, so allowing for extreme weather events such as unexpectedly violent storms.

Acceleration of stem diameter growth rate often leads also to a reduction in wood basic density (MacDonald and Hubert 2002; Guilley et al. 2004; Jaakhola et al. 2006; Cao et al. 2008; Ikonen et al. 2008; Schneider et al. 2008; Antony et al. 2009; Crous et al. 2009; Drew et al. 2009, 2011; Lasserre et al. 2009; Love-Myers et al. 2009; Warren et al. 2009; Tran et al. 2010; Savva et al. 2010; Antony et al. 2011; Gardiner et al. 2011; Watt et al. 2011; Park et al. 2012), although not always (Gaspar et al. 2009b; Gerendian et al. 2009; Kojima et al. 2009; Moore et al. 2009; Gagné et al. 2012; Guller et al. 2012). A reduction in density is often accompanied by a reduction in wood stiffness (Schneider et al. 2008; Warren et al. 2009; Watt et al. 2011), but both do not go together always (Lasserre et al. 2009; Moore et al. 2009).

This research on the effects of tree stem diameter growth rate on wood basic density and stiffness has considered both softwood and hardwood plantation species, although softwoods more commonly. It gives the general impression that faster tree diameter growth reduces wood density and stiffness, no doubt by producing wood with thinner cell walls and with larger empty spaces that the walls surround. However, this is not always the case and studies which have looked in fine detail at the properties of the individual cells produced in response to growth rate changes show that it is the relative degree of production of latewood and earlywood that often determines the final, overall average density of the wood produced. Latewood is denser than earlywood. Thus, if a higher proportion of latewood is produced when tree diameter growth rate accelerates, wood with a greater overall, average density may be produced rather than wood with lower overall density. Downes et al. (2002) attempted to describe how wood density relates to latewood and early wood development as reflected in the width of growth rings.

Gaspar et al. (2009b) considered research dealing mainly with softwoods and concluded that environmental factors such as air temperature and soil water availability determine at what time of year growth occurs and, hence, whether latewood or early wood is being produced, with its consequent effects on wood density. Wimmer and Downes (2003) reached similar conclusions for mature Norway spruce (*Picea abies*) trees growing in Germany. These conclusions are consistent with the model system developed for eucalypts mentioned earlier (Downes et al. 2009; Drew et al. 2010) where temperature and water availability were the factors assumed to drive growth rates and wood production.

An example that illustrates the effects of the balance between earlywood and latewood production was given by Gonzalez-Benecke et al. (2010) for an

11-year-old experimental plantation of loblolly pine (*Pinus taeda*) in south-eastern USA. Irrigation of the plantation from mid-summer through to late autumn led to increased tree diameter growth when compared with trees that were not irrigated. However, the irrigation only had this effect when applied late in the growing season, when the trees were producing mainly latewood. The density of the latewood itself was unaffected, but because the irrigated trees then had a higher proportion of latewood than earlywood, the overall density of the wood produced during that year was higher in the irrigated trees. Thus, faster growth resulted in higher, rather than lower, wood density.

Other studies which examined earlywood and latewood production in detail, under circumstances where tree diameter growth rates were affected by silvicultural practice, have found similar effects, with overall wood density sometimes being increased and sometimes decreased depending on the circumstances at the time growth was affected (Downes et al. 2006; Jaakkola et al. 2006; Watt et al. 2006; Cao et al. 2008; Ikonen et al. 2008; Gaspar et al. 2009b; Love-Myers et al. 2009; Savva et al. 2010; Guller et al. 2012; Medhurst et al. 2012; Park et al. 2012). Differences between temperature and water availability across various sites have also been found to have effects on wood density (Kojima et al. 2009; Stoehr et al. 2009).

Whilst much further research needs to be done, it appears at present that both silvicultural practices and climatic characteristics of a site may influence the quality of wood which is produced, particularly through their effects on water availability to trees or to the temperatures to which the trees are exposed. These effects may or may not lead to increased diameter growth rates of trees and may be accompanied by increases in, decreases in or no effects on wood properties; these influences on wood properties vary between different species and often depend on the timing of the changes in environmental effects at different times of the year. There seems to be little evidence that silvicultural effects *per se* lead to effects on wood properties. Rather, it is the effects of silviculture on the environmental circumstances of the trees that determine their wood properties. For any particular species growing under any particular circumstance, these properties will remain difficult to predict until research has provided a more thorough understanding of the physiological processes that control wood development.